Energy and Electricity Generation Notes

This presentation begins with a definition of energy, introduces a taxonomy of energy forms, offers a few relevant energy facts, and renders a very brief but illuminating snapshot of energy history. The presentation next provides a brief discussion of the various energy resources used to generate electricity, and introduces the energy resource lifecycle that must be considered when discussing the true costs of using each resource to generate electricity. Electricity-generating facility performance is then addressed for each of the energy resources.

Slide 3 – all energy comes from nuclear graphic

- graphic displays different energy forms with illustrations of how each form evolved from the nuclear particles (i.e., protons and neutrons) that formed ancient stars and our sun
- our sun and ancient stars birthed energy forms we use today – shown at bottom of graphic

Slide 4 – energy forms graphic

- energy forms categorized in variety of ways
- graphic displays different energy forms with illustrations of how each form may be manifested
  - mechanical (can be further categorized as kinetic energy or potential energy)
  - radiant (visible light only a portion of radiant, or electromagnetic, spectrum)

Slide 6 – very brief history of energy

- slide provides very brief history of energy, highlighting types of energy resources, their energy densities, and some associated benefits and shortcomings for each of three historical energy eras
- energy density of available energy resources is key to understanding evolution of human civilization
  - with development of technology came access to energy resources of greater energy density
  - energy resources of greater energy density provided humans with more abundant energy, allowing progress beyond survival mode of living
- energy density of resources also key to minimizing environmental impact while meeting ever-increasing demand for energy
- public fear of nuclear energy has restrained progress in achieving abundant, affordable, and reliable electricity for humanity that minimizes adverse effects on environment in post-industrial revolution era

Slide 7 – pre-industrial revolution energy resources

- many people today want us to go back to using only pre-industrial revolution energy resources to “save the planet” from climate change
- that will not provide enough electricity to sustain 21st century way of life for anyone, and will more than likely lead to pre-industrial revolution living conditions for mass of humanity

Slide 9 – life expectancy graphic

- graphic provides clear illustration of how advent of fossil fuels, which enabled significant improvements in sanitation, hygiene, nutrition, and medical care, led to dramatic increase in life expectancy
- mechanization of labor and electrification of businesses and households through use of fossil fuels enabled urbanization, industrialization, and increased energy consumption

Slide 13 – fossil fuels

- powered Industrial Revolution
  - enabled manufacturing of machines that made life easier for our predecessors (e.g., steam engine), and enabled technology that dominates our lives today
  - without fossil fuels, modern world would not have been possible (i.e., no hospitals, no modern medicine, no reliable summertime cooling or wintertime heating, no transportation beyond riding animals, etc.)
- continue to provide majority of our electricity needs

Slide 14 – chemical reaction

- methane is primary constituent of natural gas
- has highest energy output of all hydrocarbon fuels

Slide 16 – basic steam cycle power plant graphic

- numerous substitutes for steam as working fluid in power plant have been tried, but nothing proven more reliable, efficient, or economical than steam
- using steam as heat transfer medium means that large-power-output plant can be compact, and working fluid neither toxic nor flammable
- basic steam cycle, or Rankine cycle, produces work (power) from steam turbine
  - water boiled in furnace (boiler) using heat source such as coal to create high temperature, high pressure steam that drives steam turbine
  - low temperature, low pressure steam from turbine exhaust condensed back to water and pumped back to boiler to begin cycle over again

- work produced by spinning turbine shaft used to drive industrial machinery as well as electrical generators to produce electricity

Slide 17 – basic gas turbine power plant graphic

- basic Brayton cycle uses air as working fluid to produce work (power) from gas turbine
  - air pressurized in a compressor then heated by burning of natural gas in combustion chamber
  - high temperature, high-pressure air drives gas turbine
  - low pressure air from gas turbine exhaust cooled and directed back to compressor to begin cycle over again
- since air compressor and gas turbine have common shaft, some mechanical energy created in turbine expended in compressing air
- gas turbine power plants mainly used as standby auxiliary power units because they can be brought online rather rapidly as additional power needed by electrical grid

Slide 20 – solar energy

- U.S. government became heavily involved with solar energy research and development in 1970s, and began creating grants and tax incentives in 1990s to make rooftop solar electricity-generating systems viable and affordable for American homeowners

Slide 21 – how solar energy converted to electricity graphic

- photons exhibit different wavelengths (i.e., energies)
- no material absorbs electromagnetic energy of all wavelengths
- photovoltaic panels are most efficient in converting energy within the visible and near-infrared portion of the electromagnetic spectrum into electricity

Slide 22 – wind energy

- from 1974 through mid-1980s U.S. government worked with industry to advance wind turbine technology and enable generation of electricity from large commercial wind turbines

Slide 24 – water energy

- U.S. has over 2,000 hydroelectric power stations

Slide 25 – flowing water energy conversion graphic

- energy density of flowing water depends on difference in elevation that imparts specific velocity (speed) to water
- while energy density of moving water orders of magnitude greater than solar or wind energy density, is also orders of magnitude less than hydrocarbon fuels that empowered Industrial Revolution

Slide 27 – energy resource life-cycle graphic

- to get complete picture of cost of generating electricity from specific energy resource, one needs to look at entire energy resource conversion and utilization life-cycle

Slide 31 – waste disposal/recycling

- when entire life-cycle of energy resource used to generate electricity considered, picture that evolves with respect to affordability and environmental friendliness can be very different from claims commonly made

Slide 33 – assessing energy conversion system efficiencies

- slide illustrates process of converting primary energy source to specific energy service
- efficiencies of energy conversion devices and processes represented by Conversion Network box in middle of graphic determine overall energy conversion system efficiency
- ICT service to right of graphic is acronym for Information and Communications Technology

Slide 34 – energy conversion efficiencies

- table contains some energy conversion device efficiencies for calculating overall efficiency of electricity-generating system
- other conversion device efficiencies can be found in open literature, such as
  - nuclear reactor (nuclear energy to thermal energy)
  - PWR steam generator (thermal energy transfer)
  - industrial inverter (DC electricity to AC electricity)
  - wind turbine rotor blades (kinetic energy to mechanical energy)
  - high gear ratio gearbox (mechanical energy transfer)
  - permanent magnet generator (mechanical energy to electrical energy)
  - energy system storage battery (chemical energy to electrical energy)

Slide 35 – coal-fired power plant graphic

- graphic illustrates typical configuration for coal-fired power plant
- energy conversion devices are boiler, steam turbine, and electrical generator
- conversion device efficiencies found in energy conversion efficiencies table
- system efficiency found by multiplying energy conversion device efficiencies

Slide 36 – energy conversion efficiencies

- coal-fired power plant's energy conversion device efficiencies circled in red

Slide 37 – coal-fired power plant efficiency
- graphic is convenient template for illustrating energy conversion facility efficiencies
- minimum energy conversion device efficiencies chosen for this "non-renewable" energy resource
- note that most inefficient energy conversion device in conventional steam power plant is steam turbine
- coal-fired power plant minimum electricity-generating efficiency is 32%

Slide 38 – boiling water reactor power plant graphic
- graphic illustrates configuration of typical boiling water reactor power plant
- energy conversion devices are nuclear reactor, steam turbine, and electrical generator

Slide 39 – nuclear fission energy disposition
- slide shows how energy from U-235 fission characterized
- Approximately 90% of fission energy deposited in nuclear fuel or reactor cooling water as recoverable thermal energy

Slide 40 – nuclear power plant efficiency
- minimum energy conversion device efficiencies chosen for this "non-renewable" energy resource
- nuclear power plant minimum electricity-generating efficiency is 34%

Slide 41 – hydroelectric power plant graphic
- graphic illustrates typical hydroelectric power plant configuration
- energy conversion devices are penstock, water turbine, and electrical generator

Slide 42 – energy conversion efficiencies table
- efficiency of water turbine in converting kinetic energy to mechanical energy circled in red
- there is minimal energy loss in hydroelectric facility penstock; maximum efficiency of 95% assumed

Slide 43 – hydroelectric power plant efficiency
- maximum energy conversion device efficiencies chosen for this "renewable" energy resource
- hydroelectric power plant maximum electricity-generating efficiency is 84%

Slide 44 – photovoltaic (PV) facility graphic
- graphic illustrates typical solar panel configurations for generating electricity

- energy conversion devices are photovoltaic panel and electrical inverter

Slide 45 – Shockley-Queisser Limit graphic

- Shockley-Queisser limit of 33% is physics limit for transferring photon energy to electrons in silicon PV cells
- maximum efficiency as shown in graphic occurs in rather narrow bandgap of about 1.1 to 1.4 eV corresponding to photon energies in near-infrared portion of electromagnetic spectrum; efficiency falls off rapidly above and below this bandgap energy range
  - bandgap is energy difference between highest energy levels of valence band electrons (electrons tightly bound to atoms) and conduction band electrons (electrons that move freely) in semiconductor material
- photons with energies less than 1.1 eV largely pass through silicon or absorbed very weakly and converted into heat
- photons with energies greater than 1.4 eV can transfer necessary energy to convert valence band electrons into conduction band electrons, but excess energy converted into heat

Slide 46 – PV power facility efficiency

- efficiency of most photovoltaic panels about 20%
- while high-quality panels can exceed 22% efficiency, majority of panels do not achieve efficiencies above 20%
- typical solar inverter efficiencies range from 90% to 98%; maximum efficiency of 98% assumed
- PV power facility maximum electricity-generating efficiency is 19%

Slide 47 – wind turbine graphic

- graphic illustrates configuration of typical electricity-generating wind turbine
- energy conversion devices are turbine rotor blades, gearbox, and electrical generator

Slide 48 – Betz Limit graphic

- Betz's law defines maximum power extracted from wind, independent of wind turbine design in open flow
- figure on left of graphic illustrates Betz's law
  - horizontal axis of graph is ratio of wind turbine exit wind velocity (v_2) to incident wind velocity (v_1), where v_2 and v_1 illustrated in figure on right
  - vertical axis is power coefficient, which is ratio of extractable power to kinetic power of wind
  - Betz Limit specifies no wind turbine can capture more than ≈59% of kinetic energy of wind (when exit wind velocity is 30% - 40% of incident wind velocity)

- typically, wind turbines have maximum wind energy extraction efficiency of ≈40% (when exit wind velocity ≈70% of incident wind velocity).

Slide 49 – wind turbine power facility efficiency

- wind turbine rotor blade maximum efficiency of 40% assumed
- efficiencies of gears with high gear ratios range from 75% to 95%; assume maximum efficiency of 95%
- assume permanent magnet generator maximum efficiency of 95%
- wind turbine power facility maximum electricity-generating efficiency is 36%

Slide 51 – electricity-generating system capacity factors

- graphic illustrates capacity factors of individual U.S. electricity-generating facilities
- variation in capacity factors for coal and combined cycle natural gas reflect seasonal variations in electricity demand
  - — capacity factors decrease in spring and fall when electricity demand is generally lower
  - — capacity factors rise in summer when air conditioning increases demand for electricity
  - — fluctuations in fuel prices can also affect capacity factor
- many natural gas plants also operated for only short periods of time to provide peak load electricity, rather than baseload electricity; hence, very low capacity factors for many plants
- low capacity factors of many hydro plants result from load-following operation in which hydro power increased or decreased to meet variable electricity demand
  - — water availability also significant effect on hydro capacity factor
- low capacity factors for wind and solar facilities reflect intermittency of wind and solar energy resources for generating electricity

Slide 52 – energy system capacity factors table

- slide illustrates industry-wide average annual capacity factors for 2020
- primary influences on capacity factor are
  - — facility maintenance outages for nuclear, geothermal, coal, and natural gas facilities
  - — energy resource availability for photovoltaic and wind turbine facilities
  - — load-following operation and water availability for hydroelectric facilities
    - ✓ in addition to drought conditions, other issues that can affect water availability include flood control, navigation,

irrigation, recreation, fish and wildlife, water quality, and cultural resources

- capacity factor of 25% means that to obtain year-round average of 100 megawatts of electricity requires facility with installed capacity of 400 megawatts
  - extra 300 Mw goes to energy storage system to provide electricity when primary source not available
- table column on right shows equivalent full-power days per year each energy resource provides

Slide 54 – PV average capacity factor very misleading graphic

- capacity factors for PV and wind facilities vary significantly by geographical location, so average capacity factors shown on earlier slide are nationwide averages
- data from U.S. Energy Information Administration show that production from solar panels in some states plummets in winter, as illustrated in capacity factor graphic for state of Minnesota
- one reason for falling productivity in winter is snow cover – even thin layer of snow on panels leads to significant reductions in electricity generation
- graphic shows 2018 – 2020 average annual capacity factor for Minnesota solar PV facilities nowhere near 25%

Slide 55 – capacity factor of PV systems in some states

- graphic shows variation in PV facility average annual capacity factors for selected states
  - whereas average annual capacity factor may be as high as 29% in Arizona and Utah, can be lower than 17% in Massachusetts and New Jersey
  - average annual capacity factor for PV facilities very dependent on geographical location

Slide 56 – wind turbine system average capacity factor very misleading graphic

- capacity factors for wind facilities vary significantly by geographical location due to weather conditions (previously shown average capacity factors are nationwide averages)
- graphic shows wind turbine output versus wind speed
  - cut-in wind speed is speed at which wind turbine begins to generate output power, not wind speed at which turbine begins to operate
  - wind turbines don't produce rated power until sustained wind speed of 12 m/s (26 mph) achieved, and such sustained winds uncommon in most areas of U.S.
  - below cut-in wind speed turbines are consumers of electricity because electricity for oil pumps, hydraulic pumps, control systems, and accessories (amounting to ≈12-13% of capacity

rating) cannot be drawn from reduced turbine-generated electricity without compromising turbine safety
- wind turbine operators allowed to overstate net electricity output of systems because parasitic drain on grid ignored

Slide 57 – average annual elevated wind speed graphic
- average hub height of modern wind turbines between 90 and 100 meters
- graphic shows U.S. annual average wind speed at elevation of 100 meters based on data from 2007 to 2013 (apparently, latest data published by National Renewable Energy Laboratory in Golden, Colorado)
- in most of U.S., wind turbines produce significantly less than rated power; even in most of Great Plains, average wind speed <10 m/s (below 12 m/s required to achieve rated wind turbine output power)

Slide 58 – not all energy resources are equal
- would all like to be assured that base load electricity a function of demand and not supply
  - want lights to go on any time of day or night when light switch turned on
- likewise, would like to be assured that peak load electricity also a function of demand, not supply
  - electricity will be available during times of heavy demand, especially during summer and winter when cooling and heating needs, respectively, are highest
- for electrical grid to function, must be very close match between power supplied and power demanded, on almost minute-by-minute basis

Slide 59 – typical electricity generation usage graphic
- graphic illustrates typical daily electricity generation usage profile along with various electricity-generating sources that provide time-dependent supply of electricity to grid
- baseload generation constant because of some daily level of constant electricity demand
  - note that renewable energy resources not dispatchable (i.e., available on demand) and can't be relied upon to supply uninterrupted electricity during intermediate and peak load demand periods; therefore must be included as part of baseload electricity supply
- electricity generation must be increased to accommodate time-dependent increase in daily demand above baseload, and subsequently decreased as demand returns to baseload level
- balancing time-dependent electricity demand with supply critical to maintaining stable and reliable electricity grid

— variability of wind- and solar-generated electricity not conducive to maintaining stable and reliable grid

- **CHP** in baseload segment is combined heat and power generation (cogeneration)
- **Demand response** in peak load segment refers to strategies employed by utilities that use time-based financial incentives to modify consumer electricity consumption during periods of peak demand, power scarcity, grid congestion or anticipated grid outage

Slide 60 – typical U.S. daily electricity demand graphic

- graphic displays typical variation in daily electrical demand for New England electrical grid
- energy demand on grid varies by time of day, day of week, temperature, latitude of location, and seasons (and other factors as well)
- in graphic, seasonal baseload demand established by demand in early morning hours, between about 1 and 5 am
- morning ramp-up of electricity demand begins about 5 am, reaching intermediate demand load about 10 am, which lasts until about 10 pm; intermediate load ramp-down begins around 10 pm, ending around 1 am
- short extended peak demand loads lasting about an hour evident for fall, winter, and spring months
- extended peak demand load in summer occurs from about 3 pm to 6 pm
- spring and fall peak demand loads significantly less than winter and summer loads

Slide 61 – typical California daily demand load profile graphic

- graphic displays daily variation in California's electrical demand on hot day in 1999 and shows specific user sector demands that contributed to total electrical demand
- morning ramp-up of commercial and residential electricity demand began about 6 am and returned to baseload demand level after midnight
- extended peak electrical demand on California grid occurred from 2 to 6 pm

Slide 62 – PV panel efficiency vs time of day graphic

- graphic illustrates how power output of photovoltaic panel varies during day for both fixed (static) PV panel system and sun-tracking system
- static PV system not generally well suited to providing peak load electricity for most U.S. locations since daily time interval of PV panel peak output (noon to 3 pm) does not match well with daily time interval of peak summer demand (3 pm to 6 pm) or winter demand (6 to 7 pm)

- sun-tracking PV system with daily peak output interval of 9 am to 5 pm better match for summer daily peak demand
- although sun tracking PV system output may be suitable for meeting high air conditioning demand in middle of summer day, when sun goes down and temperature doesn't, another source of energy must be available

Slide 63 – ABQ Jewish Community Center PV system performance graphic

- graphic illustrates variability of electricity production from Albuquerque Jewish Community Center's solar photovoltaic system over 3-day period in February
- February 21 was cloudless day, with PV system producing maximum output
- February 22 experienced passing clouds that temporarily reduced system's electricity production
- February 23 overcast and Jewish Community Center had to rely on another source for electricity needs; that is, were buying electricity from Public Service of New Mexico electrical grid
- imagine Community Center difficulty in keeping lights on for windless, overcast day if fossil fuels banned and New Mexico grid consisted of only wind- and solar-generated electricity

Supplemental slide

Slide 66 – photon absorption in solar cell graphic

- free electrons produced in solar cell material having extra electrons by absorption of incident photon energy
- free electrons flow through external electrical conductor to cell material deficient in electrons, creating electric current
- direct current (DC) electricity produced in solar cells converted to alternating current (AC) electricity, using device called inverter, for transmission to electrical grid